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A High-Temperature Printed Circuit Board

by Bruce R. Geil and Merle W. DeLancey

ARL-MR-339 November 1996

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A High-Temperature Printed Circuit Board

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Abstract

Working with the U.S. Army Space and Strategic Defense Command, the Army Research Laboratory has developed an easy-to-produce, reliable, high-temperature printed circuit board for radiation studies of circuits that use silicon carbide transistors. This board is designed to operate at temperatures beyond 300°C. The board consists of an alumina substrate with thick-film gold traces. Stainless-steel pin receptacles are used to mount the transistors, allowing easy insertion and removal. Ruthenium oxide resistors are glued to the substrate and wire-bonded for electrical connection.

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1. Introduction

Recent developments in high-temperature semiconductors such as 6H-SiC have created discrete transistors that can operate at temperatures exceeding 300°C and at high levels of radiation. The Army Research Laboratory (ARL) has been working on a project for the U.S. Army Space and Strategic Defense Command (USA SSDC) to develop a radiation-hardened high-temperature amplifier circuit. The amplifier circuit is a two-stage differential amplifier that uses 6H-silicon carbide (SiC) junction field-effect transistors (JFETs) as the active devices [1,2]. This new high-temperature technology will allow electronics to be used in applications that presently require remote sensors and controls. Some of these include internal combustion engine controls, jet engine exhaust monitoring, and nuclear power applications.

The transistors are individually packaged in TO-46 headers, and hermetically sealed to prevent electrode oxidation at high-temperatures. These devices, along with other components, were required to be integrated into a small package, so that the resulting circuits would fit into the radiation test equipment. To this end, a high-temperature printed circuit board (PCB) was devised (see fig. 1). This PCB allows the discrete components, transistors, capacitors, and resistors to be wired together to produce small-area circuits.

The PCB, fabricated at ARL's Semiconductor Engineering and Materials (SEMT) facility, followed some of the techniques developed by other groups [3,4], with changes made to accommodate readily available processing techniques. This allowed rapid turnaround as needs were identified. All the techniques used in fabricating this board can be easily transferred into mass production. The PCB must withstand 300°C and be able to fit into the radiation test chamber. The PCB allows for replacement of transistors and easy testing of each circuit node at the bench.

Figure 1. Board overview.

2. Operational Amplifier PCB Development

Alumina was selected for the substrate since it is compatible with thick-film conductor pastes, can handle high temperatures (above 1000°C), and is strong enough for repeated transistor-insert cycles. To allow plug-in mounting of the packaged transistors, pin receptacles [5] from Advanced Interconnections (fig. 2) were used. The receptacles are nickel-coated stainless steel with a nickel/beryllium spring inside to allow positive contact to the transistor pins. These pin receptacles, unlike other pin receptacles, can handle the high temperatures encountered by the board. A gold-based thick-film paste, Dupont 5715, was chosen as the conducting material, since it allows use of readily available integrated circuit techniques to pattern the PCB traces. Typically, thick-film patterns are applied through a metal screen mask. Since it would require several weeks to obtain a patterned screen, the gold was applied through a blank screen, and then etched with a photopatternable mask and an iodine-based gold etch. This technique is used extensively in the production of integrated circuits. Because these standard methods were used, only one week was required for fabrication of these PCBs.

Figure 3 shows the electrical schematic, and figure 4 shows the PCB layout that was produced at the ARL SEMT facility via standard integrated circuit masking techniques. Originally, the design rules for the PCB layout specified a 1-mil line width. After one of the alumina substrates was patterned with an iodine-based gold etch (table 1), it was found that undercutting of the photoresist caused electrical shorts in the gold lines. As a remedy for this problem, the line widths were increased to 5 mils.

Figure 2. Pin receptacle design.

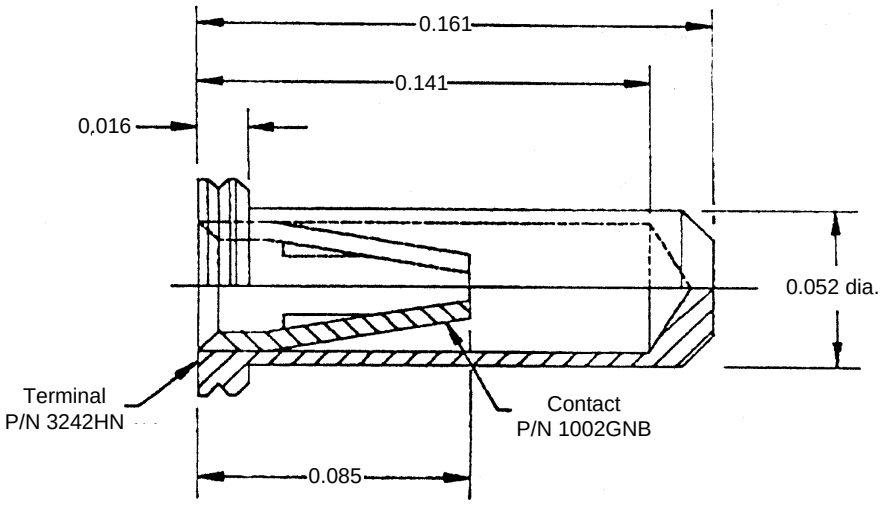


Figure 3. Board schematic.

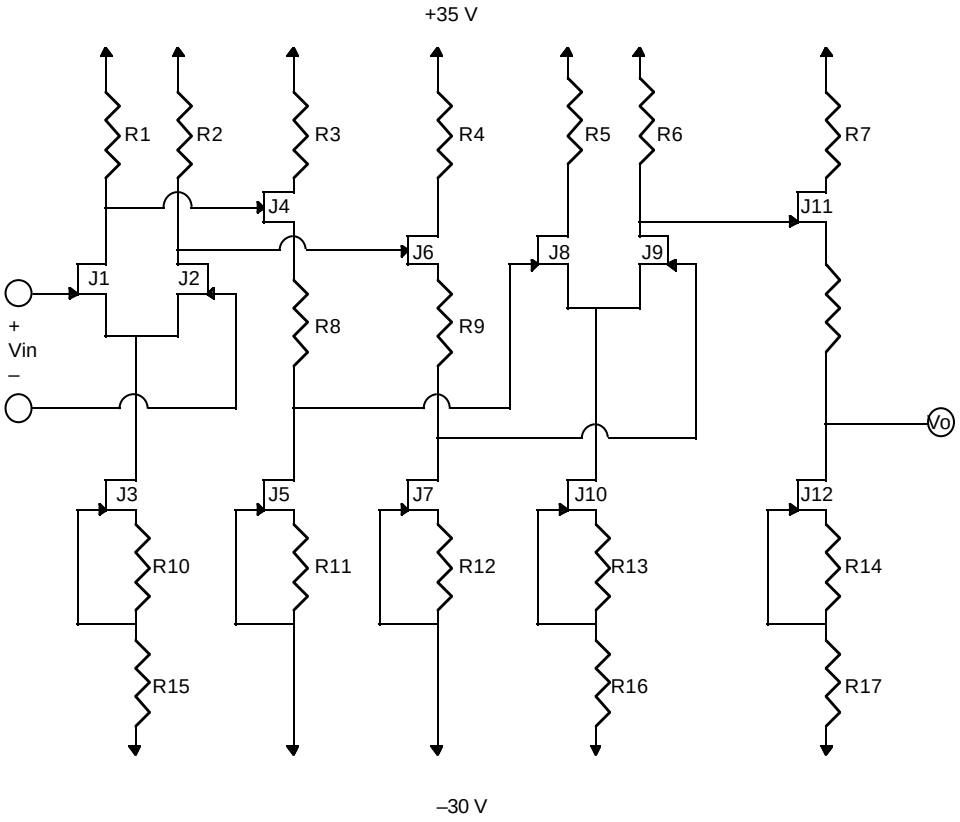


Figure 4. Mask layout.

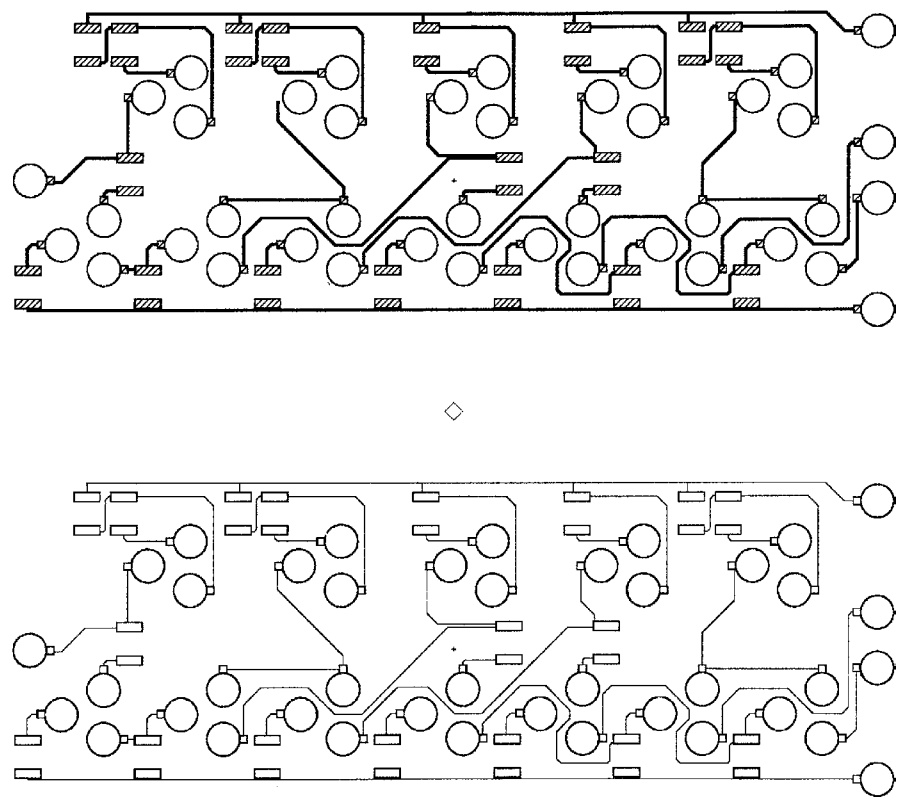


Table 1. Chemical solutions used in PCB fabrication.

Step	Solutions and processing
Nickel and gold etch	400 gm KI potassium iodide 100 gm I_2 iodine 400 ml H_2O etch rate: 400 to 1600 nm / min
Plasma ash	300–400 W, O_2 for 6–30 min
Piranha clean	100 ml H_2SO_4 50 ml DI H_2O_2 15-min dip
Posistrip 830 resist removal	15 min at 90°C
Photoresist (pulled)	KTI 825 Pull rate of 0.43 in. / min Thickness 2 µm Exposure time 30 s
Photoresist developer	200 ml Microposit 934 200 ml DI H_2O 25 s to develop
Aremco Ceramabond 571 high-temperature epoxy	10 g liquid 15 g powder Air set 4 hr Oven bake 200°F, 4 hr

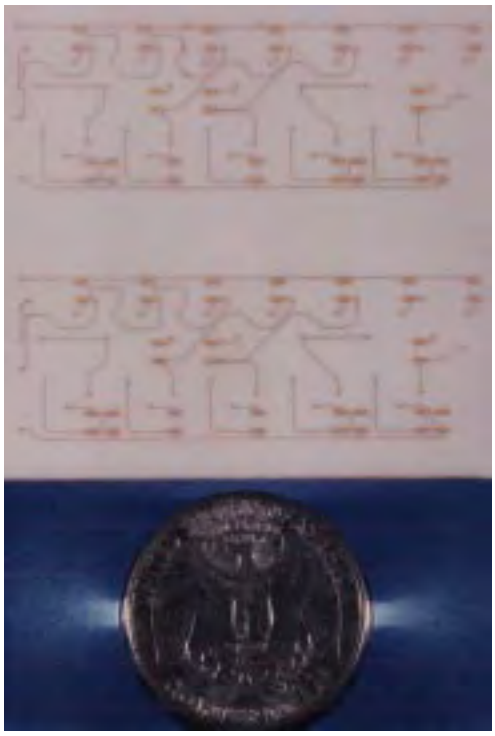
Another cause of the etch-based patterning problem was the presence of a glue layer beneath the gold film on the commercial PCBs. On two of the PCBs, the glue layer contained nickel that was partially etched during the gold-etch step; this caused the gold to lift off from the alumina substrate. To prevent this, we used substrates without the glue layer for subsequent development.

We coated several blank alumina substrates with chrome and gold using an evaporation system to deposit 1 µm of gold (fig. 5). Although the evaporated gold on these PCBs solved the problem caused by the glue layer, it did not withstand the patterning step in the PCB fabrication process and lifted off. Since these PCBs had been drilled to accept the pin receptacles, they were reprocessed with the thick-film gold instead of the thin-film process.

To prepare the substrates for the thick-film coating, we stripped the remaining gold off and cleaned them using a standard piranha cleaning process (table 1). Thick-film paste was then applied to the entire board through an unpatterned 1.1-mil screen and spread across the substrate by a squeegee. We then fired the PCBs at 800°C for 10 min to set the gold paste.

To pattern these devices, a new technique had to be used to apply the photoresist; the holes in the PCB did not allow the usual vacuum-chuck spinner to be used. A pull technique was used to apply an even coat of the resist. A clock motor was used to pull the sample out of a beaker of resist at a rate of 0.43 in. / min, giving a 2-µm resist thickness. After the resist was applied to the substrate, the PCB fabrication was then completed by the standard etch process described earlier.

Figure 5. Board after gold patterning.



Several materials were studied for use as bonding agents between the pin receptacles and the alumina PCB. The requirements for bonding these two materials together were very demanding. The bond had to hold the pin receptacles in the alumina while the transistors were being inserted or removed. The process of removing or inserting the transistor put both torsional and linear loads on the adhesive. Once the transistors had been inserted, the adhesive had to withstand 300°C operational temperatures and the thermal stress of heating and cooling. Good electrical contact had to be made between the gold traces and the pin receptacles and maintained throughout the operating regime. Another requirement for the bonding material was that it could not corrode, lift off, or otherwise damage the gold traces.

The first material studied for pin-receptacle bonding was a silver/palladium braze that had been used on other high-temperature test boards. Although the silver/palladium braze provided very good adhesion to the nickel coating on the pin receptacles and good electrical contact to the pin receptacles, it gettered the gold from the alumina PCB at temperatures above 200°C, causing shorts in the circuit.

The second material studied was Locktite Corporation's Ultra Copper™, a silicone-based automotive sealant used in high-temperature (350°C) applications such as exhaust gasketing. This material has a rubbery texture when cured and could not hold the pin receptacles in the board during insertion or removal. It also is not electrically conductive and required some other method for connecting the traces to the pin receptacles.

Two different lead/indium solders were investigated: one that melts at 295°C and one that melts at 300°C. The indium in the solder reduced the gettering of the gold while still maintaining good electrical conductivity, but did not adhere well to the nickel pin receptacles.

A mechanical method for pin receptacle retention was then studied. Small gold "C clips" were obtained that were slightly smaller than the outside diameter of the pin receptacles. The pin receptacles were inserted into the PCB, and the C clips pressed onto the pin receptacles on the back of the PCB. These C clips provided good pull-out strength but little or no torsional strength. To provide the torsional strength, we placed Dupont 5715 gold thick-film conductor around the C clip to anchor it to the pin receptacles. A small amount of the gold conductor was then used to make electrical connection from the pin receptacles to the traces on the front side of the PCB. The gold thick-film paste was applied between the pin receptacles and the gold traces, and the PCB fired at 800°C for 1 min. Although this method did provide good electrical conduction, it had some problems with mechanical strength. Even with the gold thick-film paste, the rotational strength of the joint was not good enough to prevent several of the pin receptacles from rotating during transistor placement, breaking the electrical connection.

The method finally chosen to attach the pin receptacles to the PCBs involved the use of a high-temperature adhesive for the mechanical bond and gold paste for the electrical bond. Aremco Ceramabond 571 adhesive was chosen since it has good adhesion to both the nickel pin receptacles and the alumina substrate. It also has a coefficient of expansion midway between that of alumina and the stainless steel pin receptacles (table 2).

The first part of the process was to make contact to the pin receptacles with a small amount of gold paste. The paste was applied to the trace at the edge of the hole through which the pin receptacles were inserted. When the pin receptacles were pushed through the hole, the lip at the top of the pin receptacles was pushed into the gold paste. Once the pin receptacles were inserted into the hole, the PCB was flipped over and Aremco Ceramabond 571 [6] high-temperature adhesive applied. After a 2-hour air cure and a 2-hour 93°C cure for the adhesive, we fired the PCB at 700°C to activate the gold paste and create the electrical connection between the pin receptacles and the PCB (fig. 6).

The other major requirement for this PCB was resistor mounting. It was found early in the development of this design that the ruthenium resistors used for hybrid circuits would maintain good tolerance over the entire temperature range. We decided to use available surface mount resistors instead of producing these resistors directly on the PCB.

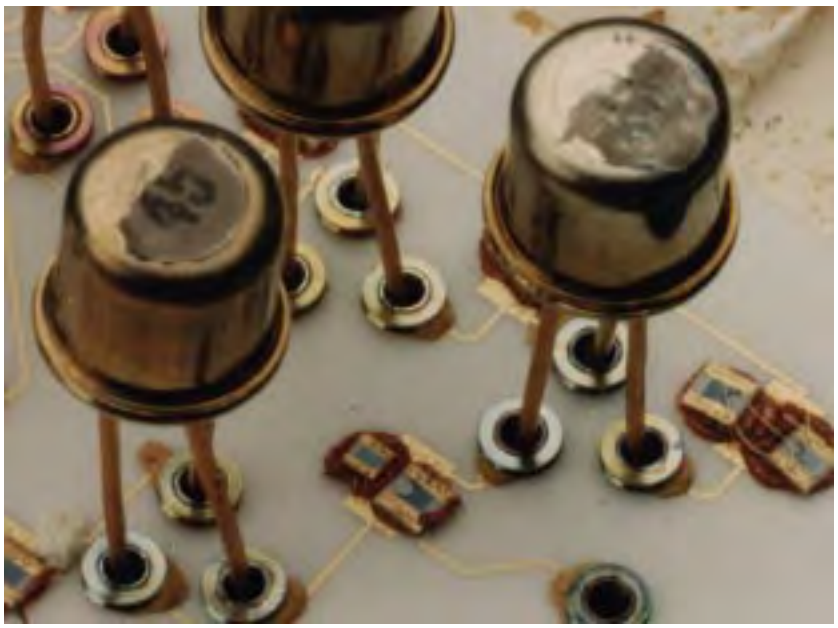
Since the resistors were surface mounted to the board and not trimmed directly, the following method was used to locate the resistors necessary to meet the required <5-percent tolerance. We chose several values of 5-percent resistors and tested them at both room temperature and at the 300°C operating temperature. Once testing was completed, a computer

Table 2. Aremco high-temperature ceramic adhesive properties.

Characteristic	Value according to product No.			
	503	516	552	571
Major constituent	Alumina	Zirconia	Alumina	Magnesia
Temperature limit				
(°F)	3000	3200	3000	3200
(°C)	1650	1760	1650	1760
No. of components	1	1	1	2
Relative viscosity (CPS)	30–40M	20–30M	37–50M	50–60M
CTE[a]				
(in./°F × 10^{-6})	4.0	4.1	4.3	7.0
(in./°C × 10^{-6})	7.2	7.4	7.7	12.6
Volume resistivity				
(W-cm at room temp.—RT)	10^8	10^8	10^8	10^9
(W-cm at 1000°F)	10^5	10^4	10^4	10^5
Thermal conductivity (BTU)	48.8	16.3	49.8	75.6
Dielectric strength				
(V / mil at RT)	253	250	250	255
(V / mil at 1000°F)	240	80	80	100
Torque strength (ft-lb)	5.6	8.6	6.7	22.3
Hardness (Moh's scale)	6	6.5	7	5.5
Porosity (after curing) (%)	<1	<1	<1	<1
Oxidation resistance	Excellent	Excellent	Excellent	Excellent
Alkali resistance	Fair	Excellent	Excellent	Excellent
Acid resistance	Excellent	Good	Good	Fair
Attacked by	HF	HF & H_2SO_4	Concentrated HF	HF
Solvent resistance	Excellent	Excellent	Excellent	Excellent

[a]*Coefficient of thermal expansion*

Figure 6. Closeup of resistor and pin receptacle mounts.



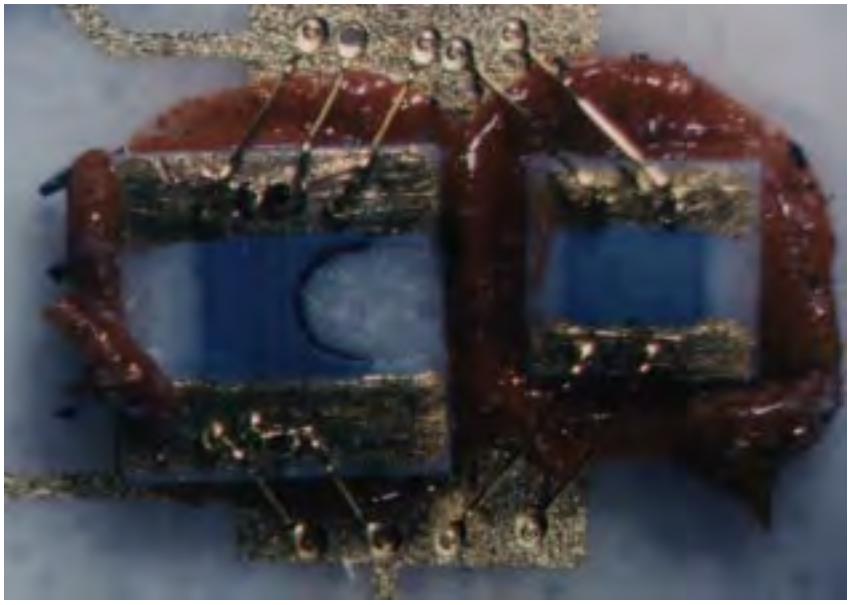
program was written to match these resistors with the required values. This program chose one or two ruthenium resistors for each of the required resistors, and indicated whether the resistors should be wired in parallel or series. In all cases, the values were kept to within 2 percent of the required value at 300°C.

The resistors were attached to the PCB with Ultra Copper™. While allowing a maximum operating temperature of 350°C, Ultra Copper™ also permits the resistors to be easily removed for PCB repair and/or modification. The electrical connections to the resistors were made with 1-mil gold wire bonds. Figure 7 shows a closeup of the resistor bonding technique.

3. Conclusion

Two PCBs have been constructed under this program. The first PCB was used in the construction of the high-temperature radiation-hard amplifier circuit, and the second was kept as a spare. The amplifier PCB has had several transistors inserted and removed through several cycles, with no PCB connection failures to date. At this writing, this PCB has been intermittently operated at temperatures exceeding 300°C for more than 100 hours, with no thermal stress failures of the board.

Figure 7. Closeup of resistor mounting.



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